

No X-rays from WASP-18.

Implications for its age, activity, and the influence of its massive hot Jupiter

Ignazio Pillitteri^{1,2}, Scott J. Wolk², Salvatore Sciortino¹, and Victoria Antoci³

¹ Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy
e-mail: pilli@astropa.inaf.it

² SAO-Harvard Center for Astrophysics, 60 Garden St, Cambridge, MA, 02138, USA

³ Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark.

Received; accepted

ABSTRACT

About 20% out of the > 1000 known exoplanets are Jupiter analogs orbiting very close to their parent stars. It is still under debate to what detectable level such *hot Jupiters* possibly affect the activity of the host stars through tidal or magnetic star-planet interaction. In this paper we report on an 87 ks *Chandra* observation of the hot Jupiter hosting star WASP-18. This system is composed of an F6 type star and a hot Jupiter of mass $10.4 M_{Jup}$ orbiting in less than 20 hr around the parent star. On the basis of an isochrone fitting, WASP-18 is thought to be 600 Myr old and within the range of uncertainty of 0.5-2 Gyr. The star is not detected in X-rays down to a luminosity limit of 4×10^{26} erg/s, more than two orders of magnitude lower than expected for a star of this age and mass. This value proves an unusual lack of activity for a star with estimated age around 600 Myr. We argue that the massive planet can play a crucial role in disrupting the stellar magnetic dynamo created within its thin convective layers. Another additional 212 X-ray sources are detected in the *Chandra* image. We list them and briefly discuss their nature.

Key words. stars: activity – stars: coronae – stars: individual (WASP-18)

1. Introduction

About 20% of the > 1000 extra-solar planets discovered to date are hot Jupiters, meaning massive planets orbiting at a few stellar radii from the parent stars. Models predict that hot Jupiters could affect the activity of their host stars through either tidal or magneto-hydrodynamical interaction (e.g. Cuntz et al. 2000 and Ip et al. 2004). Both effects strongly scale with the separation d between the two bodies (Saar et al. 2004)). Observational evidence for star-planet interaction (SPI) was first reported by Shkolnik et al. (2003), who discovered variability in the chromospheric activity indicators, the H&K lines of Ca II of HD 179949, phased with the planetary motion. Subsequently, Fares et al. (2010) reconstructed the magnetic field of HD 179949, and confirmed periodic variations of chromospheric activity indicators (H α and Ca II lines) synchronized with the beat period of the planet-star system.

In the X-ray band, Kashyap et al. (2008) showed that stars with hot Jupiters are statistically brighter by up to a factor four than stars with distant planets. Krejčová & Budaj (2012) support the findings of Kashyap et al. (2008) by means of a survey of Ca II H&K lines on planet hosting stars that traces a relationship between stellar activity and planet-star separation, with closer hot Jupiters orbiting more active stars. However, Poppenhaeger et al. (2010) and Poppenhaeger & Schmitt (2011) argue that the above results are biased by selection effects, and SPI is not a common phenomenon, rather SPI manifests itself only in peculiar cases.

One of the clearest cases of detection of SPI is HD 189733. We have observed this system three times with *XMM-Newton*

and found strong evidence of SPI at work in X-rays (Pillitteri et al. 2010, 2011, Pillitteri et al. 2014, submitted to ApJ). The first evidence comes from the overall activity of the host star. The very low level of X-ray activity of the M type companion, HD 189733B, puts a strong constraint on the age of the system at ≥ 2 Gyr (Pillitteri et al. 2010; Poppenhaeger et al. 2013). Supported also by the 2011 and 2012 *XMM-Newton* observations, the old age of HD 189733B is reinforced by the fact that it does not show flaring variability on a time scale of a few hours and within the *XMM-Newton* exposures (30 – 50 ks), as in young or active M-type stars. The old age of the secondary is inconsistent with the young age of the system as derived from stellar activity of HD 189733A, which is of order 600 Myr (Melo et al. 2006). Schröter et al. (2011) have reported a similar result on Corot-2A. Based on *Chandra* observations of a planetary transit, they find that the primary is X-ray bright with a luminosity $\sim 1.9 \cdot 10^{29}$ erg s⁻¹, indicating an age < 300 Myr, while a potential stellar companion of Corot 2A is undetected down to a limit of $L_X \sim 9 \cdot 10^{26}$ ergs s⁻¹, implying a much older age.

In main sequence stars, coronal activity is tightly linked with the internal structure of the stars, because of the link between convective zone, dynamo action and magnetic field emergence. Stellar activity is a handle for understanding the depth of the convective zone and the efficiency of the dynamo. In stars with intermediate masses, approximately from late A-type stars and moving toward earlier types, the thin convective layer disappears, and so do magnetic dynamo and coronal emission. The precise onset of the convection is a function of the mass, the chemical composition, which affects the opacity of the inner layers of the

star, and the stellar evolutionary stage. Mid F-type stars like our target, WASP-18, should possess a thin convective layer that can still generate an $\alpha - \omega$ dynamo similar to the solar one and produce a X-ray bright corona. In fact, mid and late F stars are X-ray bright in young clusters like the Hyades (600 Myr) at a level of $L_X > 10^{28.5}$ erg/s. In the framework of the relationship between age, rotation, convective zone depth, dynamo and coronal activity, the emission of X-rays in this range of masses is a probe of the dynamo efficiency from thin convective layer coupled with the rotation of the star. In late F-type stars with hot Jupiters at the age of Hyades, an enhancement of the X-ray activity should be then expected.

1.1. WASP-18

With the intent of exploring SPI as a function of the star-planet separation in a star with shallow convective zone, we observed the system of WASP-18 with *Chandra* for a whole orbital period of its planet. WASP-18 (HD 10069, 2MASS J01372503-4540404) is a F6 star at ~ 100 pc from the Sun that harbors a very close-in hot Jupiter, with the planet orbiting in only 19.4 hours (Hellier et al. 2009). The main characteristics of this system are given in Table 1 and are obtained from a recent spectroscopic study by Doyle et al. (2013). Numerous optical spectroscopic observations allowed quite precise estimates of the effective temperature, gravity, distance, chemical abundances and mass of WASP-18 (Doyle et al. 2013).

WASP-18b has a mass of about $10.43 M_{Jup}$ and a density $\rho = 6.6 \rho_{Jup}$. Due to a star-planet separation of only $3.48 R_*$ (0.02047 AU), the planet is experiencing strong irradiation that heats and bloats its atmosphere and fills its Roche lobe. Southworth et al. (2009) estimate an equilibrium temperature of about 2400 K. The close separation suggests that the planet is on the verge of the final spiralling phase toward the parent star and this gives an opportunity to observe the final phases of a planet before destruction (Brown et al. 2011).

While WASP-18 was known to have low activity based on the $\log R'_{HK}$ indicator, the remarkably close separation between planet and star demands further studies of this system to explore the effects of SPI, both of tidal and magnetical origin. A star with an age of 600 Myr is expected to have a level of X-ray luminosity typical of that of Hyades ($L_X \sim 10^{28.5} - 10^{29.5}$ erg/s, Stern et al. 1995; Randich & Schmitt 1995). Despite this range of presumed X-ray luminosity, WASP-18 was undetected in a 50ks stacked *Swift* exposure (Miller et al. 2012) at a limit of $\log L_{X,lim} = 27.5$, and in the ROSAT All Sky Survey (which has an typical sensitivity of $\log f_X \geq 10^{-12}$ erg s $^{-1}$ cm $^{-2}$).

In this paper, we report the absence of detected X-ray emission from WASP-18 in a 87 ks deep *Chandra* exposure, and its implications for the models of star-planet interaction and the evolutionary stage of this system. The structure of the paper is as follows: Sect. 2 describes the information on the age of WASP-18, Sect. 3 describes the observations and data analysis. Sect. 4 reports our results. Finally, In Sect. 5 and 6 we discuss the results and draw our conclusions, respectively.

2. Age of WASP-18

With respect to our investigations the age of WASP-18 is a critical parameter, hence in this section. we discuss it in details. Estimating the age of a star is a difficult task, and best applied to a statistical sample like stars belonging to open clusters. Methods for dating the age of stars are semi- or fully empirical and rely

on gyrochronology, rotation and activity tracers, or on isochrone fitting or asteroseismology, this latter especially used for solar-like oscillators and red giants (Soderblom 2010). It is observed that stars during the main sequence phase lose angular momentum through magnetized stellar winds so that for single stars it is possible to estimate their age from their rotation (Skumanich 1972). Historically, activity tracers have been the Ca II H&K lines, Mg II h&k lines and H α line (Wilson 1966; Vaughan & Preston 1980; Baliunas et al. 1995). All of them are sensitive to the chromospheric contribution to the line that is related to the overall stellar activity. Again, the connection between activity and rotation and between rotation and age makes the measurements of these lines an empirical method to estimate the stellar age. However, in the cases of stars with hot Jupiters, the rotation and the activity tracers can be affected by the interaction with the planet, thus biasing the estimate of the age of the host star. Pillitteri et al. (2010, 2011); Poppenhaeger et al. (2013); Pillitteri et al. (2014); Poppenhaeger & Wolk (2014) and Schröter et al. (2011) have found that the hot Jupiter hosting stars HD 189733 and Corot-2A have likely been spun up by their close in planets, and thus their activity and rotation have been enhanced, mimicking thus the behavior of younger stars. In HD 189733, activity tracers like X-ray luminosity would assign an age in the range 0.6-1.1 Gyr (Melo et al. 2006; Sanz-Forcada et al. 2011), while the stellar companion is much older. On the same star, Torres et al. (2008) used fitting to Y^2 isochrones (Demarque et al. 2004; Yi et al. 2001) to estimate an age of $\tau = 6.8^{+5.2}_{-4.4}$ Gyr.

The low chromospheric activity of WASP-18 would assign to it an age similar to that of the Sun or older. On the basis of isochrone fitting, the age of WASP-18 has been estimated by Hellier et al. (2009) and Southworth et al. (2009) to be similar to that of the Hyades but this estimate has a large range of uncertainty. Southworth et al. (2009) studied in details the stellar parameters of WASP-18 employing several models of stellar evolution: models from Claret and collaborators (Claret 2004, 2005, 2006, 2007), Y^2 models (Demarque et al. 2004; Yi et al. 2001), and *Cambridge* models (Eldridge & Tout 2004; Pols et al. 1998). The parameters from various models agree well (less agreement is found for the results from *Cambridge* models) but overall the age of WASP-18 is found in the range from 0.5 to at most 2 Gyr. We will assume this range of age for WASP-18 and in Sect. 4 we will compare these values against the evidences of an older stellar age. For a star in the 0.5-2 Gyr age time interval, corresponding to an age between that of the Hyades and of stars in NGC 752 open cluster, the X-ray luminosity of late F stars should be approximately in the range $28.1 < \log L_X < 29.5$ (Pallavicini et al. 1981; Stern et al. 1995; Randich & Schmitt 1995; Giardino et al. 2007).

3. Observation and data analysis

We observed WASP-18 ($\alpha = 1^h 37^m 24.2^s$, $\delta = -45^\circ 40' 40.3''$, J2000) using *Chandra* with a continuous ~ 87 ks long observation with ACIS camera. ACIS CCDs number 1, 2, 3, 6, 7 were used. WASP-18 falls in the CCD nr. 3 (see Fig. 1). The star is not visible in the X-ray image, and is not detected at a significance threshold of 4σ of local background, after applying a wavelet detection algorithm (Damiani et al. 1997b,a, 2003). The significance threshold of 4σ is the value usually adopted to have statistically at most one spurious source per field. We have also run the detection algorithm at a significance threshold of 3σ but still no sources are found within $5''$ from the nominal position of the star. We tested the hypothesis that WASP-18 could be heavily embedded in the material stripped from the outer atmosphere of

Table 1. Main properties of the WASP-18 system. Photospheric data from Doyle et al. (2013), other data from the catalog at *exoplanet.eu*. The range of age is from Southworth et al. (2009)

Name	Type	Mass	Radius	Distance	T_{eff}	V	Age
WASP-18	F6IV-V	$1.28 \pm 0.09 M_{\odot}$	$1.29 \pm 0.16 R_{\odot}$	100 ± 10 pc	6400 ± 75 K	9.3 mag	$0.63 (0.5 - 2 \text{ Gyr})$
Name	Type	Mass	Radius	Period	Semi-major Axis	Note	
WASP-18b	hot Jupiter	$10.4 \pm 0.4 M_{\text{Jup}}$	$1.165 \pm 0.077 R_{\text{Jup}}$	$0.9414518 \pm 4 \times 10^{-7}$ d	0.0205 ± 0.0004 AU	Transiting	

the planetary companion. In this case the gas absorption should attenuate the soft part of the spectrum ($kT < 1$ keV), leaving any hard component spectrum still detectable. For this purpose we applied the same source detection procedure on the image in the 1.5–5.0 keV band without successful detection of any source at the position of WASP-18. Hence we exclude that WASP-18 is shrouded in X-rays by a dense gas layer from its hot Jupiter. At this point, we have calculated an upper limit to the rate in 0.3–8.0 keV consistent with the 3σ threshold, this value is 3.8×10^{-5} counts s^{-1} .

Table 2 reports the positions, offaxis, significance, counts, count rates, and exposure times of 212 detected sources detected above the 4σ threshold. We have cross-correlated the positions of the detected sources against NED, 2MASS and Simbad catalogs in order to identify optical and IR counterparts. Table 4 reports the list of matches with notes about their nature. For the brightest sources we have also extracted the spectra, and performed a best fit adopting either an absorbed thermal model or an absorbed power law with XSPEC software ver. 12.8. Table 5 lists the best fit parameters.

We obtained an archival FEROS spectrum of WASP-18 acquired on Sept. 9th 2010, in particular we examined the portion of spectrum around H_{α} and Lithium doublet (6708Å). We estimated the rotational period of WASP-18 by deriving the projected rotational velocity $v \sin i$. We measured the gaussian full width at half maximum of the weak Fe lines around Li doublet equal to $FWHM = 0.42$ Å. We corrected this value by quadratically subtracting: a) 0.14 Å of instrumental resolution, b) 1 km/s of micro turbulence, and c) 4 km/s of macro turbulence. The values of micro and macro turbulence are broadly consistent with those used by Doyle et al. (2013). We assumed that the axis of the planetary orbit aligned with the stellar rotational axis and a angle between orbital plane and line of sight $i = 86 \pm 2.5$ deg to obtain a value of rotational velocity $v \sim 17.2 \pm 0.5$ km/s. Given a stellar radius of $1.29 R_{\odot}$, the rotational period is $3.7 - 3.9$ days, which makes WASP-18 a moderate rotator. However, Doyle et al. (2013) report a slower $v \sin i$ (10.9 ± 0.7 km/s) which would give a period of $P \sim 6$ days. The discrepancy of our period (3.7–3.9 d) and that inferred by Doyle et al. (2013) does not produce disagreement in the expected activity of WASP-18. For a star of the mass of WASP-18 and rotating in about 4–6 days, the expected X-ray luminosity should be $L_X \geq 10^{29}$ erg s^{-1} (see Fig. 5 and Fig. 8 in Pizzolato et al. 2003).

4. Results

4.1. No X-rays from WASP-18

As stated in Sect. 2, WASP-18 is not detected in X-rays. The limiting count rate is $r_{\text{lim}} = 3.8 \times 10^{-5}$ ct s^{-1} . By using PIMMS software we can estimate a limiting flux and luminosity from the upper limit to the rate. We assumed a thermal spectrum with one temperature at $kT = 0.5$ keV in analogy with HD 189733 and the plasma temperatures typical of young Hyades, and a gas absorption equal to $N_H = 1.5 \times 10^{20}$ cm^{-2} . We obtain a limit unabsorbed flux of 3.8×10^{-16} erg s^{-1} cm^{-2} in 0.3–8.0 keV band,

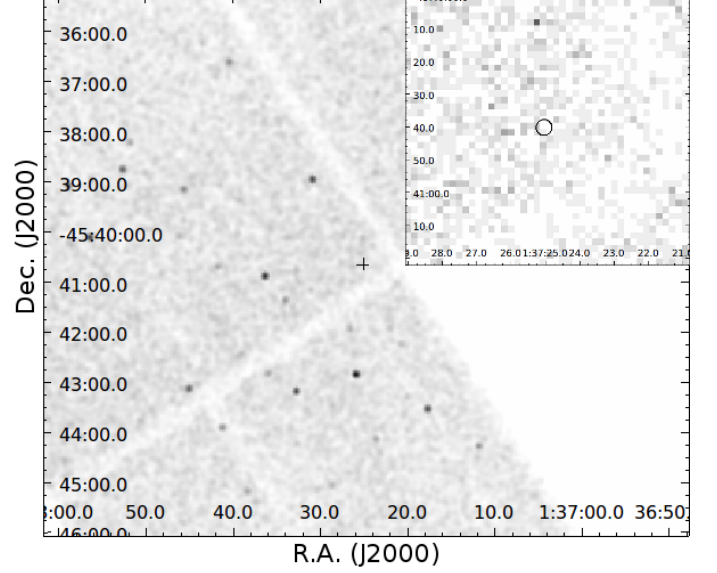


Fig. 1. *Chandra*-ACIS image toward WASP-18. The cross marks the position reported in SIMBAD database. The inset image at the top right corner shows the region around the star, with the circle marking the position of WASP-18.

which corresponds to a luminosity of $L_X \leq 4.5 \times 10^{26}$ erg s^{-1} at a distance of 100 pc. In the case we use a softer spectrum ($kT = 0.3$ keV) the limiting flux and luminosity would be $f_X = 5.9 \times 10^{-16}$ erg s^{-1} cm^{-2} and $L_X = 1.5 \times 10^{27}$ erg s^{-1} , respectively. The L_X value are surprisingly low for a star whose age is estimated to be around 600 Myr like the Hyades. late F stars in Hyades have a median luminosity of $L_X = 10^{29}$ erg s^{-1} with a dispersion of about 0.5 dex (Randich et al. 1998; Stern et al. 1995; Randich & Schmitt 1995).

Even older F type stars can emit more X-ray luminosity than WASP-18. For comparison, we report the serendipitous detection in X-rays of the F6V type star HD 110450, in a 20ks exposure devoted to observe R Mus (P.I. N. Remage Evans, Pillitteri et al. in prep). HD 110450 is very similar to WASP-18: it is at ~ 100 pc from the Sun, and has an age estimated between 2.1 Gyr and 3.9 Gyr (Casagrande et al. 2011; Holmberg et al. 2009). In X-rays, it has a PN rate of 20 ct/ks in 0.3–8.0 keV band, the best fit to the spectrum gives a temperature of $kT = 0.2$ keV and $N_H = 3 \times 10^{21}$ cm^{-2} , unabsorbed flux of $f_X = 2.5 \times 10^{-13}$ erg s^{-1} cm^{-2} and luminosity $L_X = 3.1 \times 10^{29}$ erg s^{-1} . From this comparison, we conclude that were WASP-18 coeval of HD 110450, its low X-ray activity would be still at odds with that of a typical F-type star. The inactive F5 type star Procyon and the F7 type hot Jupiter host τ Boo have an X-ray luminosities $\log L_X \sim 28$ and $\log L_X = 28.8$ respectively. More interestingly, WASP-18 and τ Boo have similar rotational periods, 3.7–6 days for WASP-18, and 3.1–3.7 days for τ Boo (Catala et al. 2007). A similar level of X-ray activity should be observed because of the link between rotation and X-ray activity (Pallavicini et al. 1981; Piz-

Table 2. List of X-ray sources detected in the ACIS image. Only ten rows are shown here, the full table is available in electronic format only.

num.	R.A. (J2000) deg	Dec (J2000) deg	Pos. err arcsec	Off-axis arcmin	Significance σ_{bkg}	Counts cts	Cts err.	Rate ct ks ⁻¹	Rate err.	Exp. time ks
1	24.23177	-45.54562	8.4	9.78	4.45	69.51	21.66	1.99	0.62	34.93
2	24.24039	-45.58173	2.5	7.77	4.13	18.18	7.29	0.296	0.119	61.37
3	24.24631	-45.52741	3.3	10.46	4.38	24.7	9.64	0.79	0.308	31.25
4	24.25307	-45.62677	1	5.41	9.44	30.27	9.06	0.399	0.119	75.95
5	24.26107	-45.64003	0.8	4.66	4.77	7.54	4.5	0.123	0.073	61.51
6	24.26128	-45.59062	1.9	6.83	4.2	13.33	5.74	0.183	0.079	72.66
7	24.26154	-45.59641	2.5	6.54	4.39	18.43	7.22	0.249	0.097	74.09
8	24.26997	-45.53962	2.2	9.4	12.45	76.95	11.65	1.359	0.206	56.61
9	24.27015	-45.62587	1.4	4.93	8.56	32.49	9.56	0.409	0.12	79.52
10	24.27129	-45.58701	2	6.79	7.52	35.92	10.77	0.487	0.146	73.81

zolato et al. 2003). However, the age of τ Boo is estimated around 2 Gyr, and its activity is perhaps boosted by magnetic SPI (Walker et al. 2008). WASP-18 stands out of the typical activity of similar mass stars. Summarizing, WASP-18 is more than 2.5 orders of magnitude less luminous than Hyades, and about 2 orders of magnitude less active than the twin HD 110450, the inactive Procyon and the similar planet host τ Boo. The absence of X-ray activity in WASP-18 is in agreement with the very low chromospheric activity reported by Knutson et al. (2010) and Miller et al. (2012), that report the not detection of this star in a 50 ks stacked *Swift* exposure at $\log L_{Xlim} = 27.5$. Its low activity would suggest a much older age, of a few Gyr, because of the relationship between activity-rotation-age in main sequence stars, and hence an age comparable to that of the Sun or older. Yet, the isochronal age estimate of WASP-18 appears plausible given the agreement of several stellar models (Southworth et al. 2009). At odds with an age older than 2 Gyr is also the moderately high rotational rate of WASP-18. The contradicting age estimates of WASP-18 imply that even an old age alone cannot explain the darkness of WASP-18 in X-rays. This points out to a role played by its close massive hot Jupiter.

5. Discussion

The first unexpected result we have obtained with the 87 ks *Chandra* exposure is the very low upper limit to the X-ray luminosity of WASP-18 ($L_{Xlim} = 4.5 \times 10^{26}$ erg/s). The lack of X-ray and chromospheric activity of WASP-18 is inconsistent with its young age. Indeed the comparison with Hyades and with the similar stars, like HD 110450, τ Boo and Procyon, points to an age much older than that given by Hellier et al. (2009). Optical spectra obtained at ESO telescope with the FEROS spectrograph confirm absence of activity and suggest an age similar or older than that of the Sun (Soderblom 2010). Fig. 2 shows the portion of one of the FEROS spectra around H α . The line is seen completely in absorption, with no signs of filling-in of the core that could be due to chromospheric activity. Moreover, the many weak absorption lines of Fe and other metals are quite narrow meaning a slow stellar rotation. Altogether these features demonstrate the low activity of WASP-18, and would suggest an age more closer to that of the Sun. Using the empirical calibration given by Soderblom (2010), despite its limitations, and the value of $\log R'_{HK} = -5.43$ reported by Knutson et al. (2010), gives us an age $\tau \geq 2.7$ Gyr. The chromospheric activity indicator of WASP-18 is even below the average value of M67 cluster (4.5 Gyr, Soderblom 2010) and the solar value.

However, the scenario becomes more puzzling when considering that WASP-18 shows Li absorption at 6708 Å, with a value typical, or even stronger than values found in F-late stars of Hyades (Takeda et al. 2012) and M67 (Pace et al. 2012). Fig. 3 shows a portion of the spectrum of WASP-18 around the Li doublet lines at 6708 Å, and Fig. 4 shows the Li equivalent widths (EWs) vs. T_{eff} given by Pace et al. (2012) and Takeda et al. (2012) for Hyades and the older M67 cluster. For comparison we show the FEROS spectrum of τ Boo which has no Li absorption. The Li absorption in WASP-18 suggests a younger age with respect to τ Boo or a different efficiency in the mixing mechanism among these two stars of similar effective temperatures and masses. In WASP-18 the equivalent width (EW) that we have measured is $EW(Li) = 46 \pm 2$ mÅ.

Compared to the values reported by Takeda et al. (2012) and Pace et al. (2012), WASP-18 has a slightly higher Li abundance. Lithium depletion is due to the convective mixing during the main sequence life of a star hence Li abundance is a rough indicator of youth in solar type stars with deep convective zone. In more massive stars, the mixing is less effective in bringing Li at the burning temperatures (2.5×10^6 K). However in mid F type stars Li abundance shows a significant dip that is still not well understood. The dip appears between 6700 K and 6200 K (see Fig. 3), with a steep edge on the hot side and a slower rise on the cool side. WASP-18 is in this range of temperatures ($T_{eff} \sim 6400$ K) and should have a low Li abundance.

Israeli et al. (2004) claim that stars harboring hot Jupiters have Li abundance lower than single stars, similar results were reported by Gonzalez (2008) and Delgado Mena et al. (2014). Bouvier (2008) qualitatively explains this result by tracing it back to the Pre Main Sequence (PMS) history of the angular momentum of the star+disk system. A long lived circumstellar disk during PMS creates a slow stellar rotator with a strong shear at the base of the convective zone and a more efficient mixing that accelerates the Li burning. At the same time, a long lived disk offers more favorable conditions for the formation and the migration of exoplanets. WASP-18 has a significant Li abundance conflicting with the general pattern of Li in stars hosting hot Jupiters.

How to reconcile the X-ray darkness, the absence of activity, an old age and with the “high” Li abundance in WASP-18? The solution to these conflicting evidences could rely in the strong tidal interaction between the massive planet and its host star. We speculate that the tidal interaction in WASP-18 could interfere in a significant way with the upper layers of the convective zone to the point to cancel out the magnetic activity and to reduce the mixing of the stellar material. Following Cuntz et al. (2000),

we estimated a height of the tide of $H_t \sim 498$ km. This value could still be a small fraction of the depth of the convective zone ($\sim 16\%R_*$, Houdek et al. 1999; Trampedach et al. 2013). However, the depths of the convective zone in stars of mass of WASP-18 or higher are very sensitive to the mass and temperature and in this range of temperatures its calculation suffers of significant uncertainties (see Claret 2004). WASP-18 has the large ratio between tide height and pressure scale height (H_t/H_p), being of order of 1.2 as shown in table 3, where we list the ratios H_t/H_p of a sample of stars with hot Jupiters with effective temperatures T_{eff} in the range 6200 – 6600 K taken from Knutson et al. (2010). The H_t/H_p ratio takes into account the tidal effect due to the mass of the planet and its distance from the star (through H_t) and the properties of the star (T_{eff} , stellar mass and radius through H_p). We speculate that the tides on the stellar surface could influence the convective motions and the meridional circulation inside the convective layers to effectively reduce or nullify the mechanism of magnetic dynamo. The ratio H_t/H_p could be an empirical parameter of the efficiency of the planetary tide in reducing the shear within convective layers. The difference of Li in WASP-18 and τ Boo could be a manifestation of different tidal interactions in these two systems. It has been observed that in tidally locked binaries of Hyades Li is more abundant than in single stars pointing to a role of tidal influence on the inner mixing of these stars (Thorburn et al. 1993; Deliyannis et al. 1994).

The existence of WASP-18b poses a strong constraint on the models of the dynamics of planets migrating inward. If the stellar age is in the range 2-4 Gyr, the inward planet migration has acted on a time scale of a few Gyr, not on a time scale of hundreds of Myr as derived by Brown et al. (2011). Hence the orbital evolution of WASP-18 b has been slower than predicted by models of orbital evolution of hot Jupiters. The low activity of the star has also consequences for the photo-evaporation of the planet and its lifetime. An X-ray and UV flux two orders of magnitude weaker than in other systems like τ Boo and HD 189733 produce much less evaporation of the upper layers of the planetary atmosphere, making the process slower than in other active hosts of hot Jupiters (Penz & Micela 2008; Sanz-Forcada et al. 2011). We expect that Roche-Lobe enhancement of the evaporation (Erkaev et al. 2007) should not be important in WASP-18b given its mass ($\sim 10.4M_{jup}$).

The absence of a significant corona explains why the star is dark in X-rays. WASP-18 demonstrates that SPI of tidal and magnetic origin must depend on both stellar structure and evolutionary stage. A different example of SPI in a star with a very close-in hot Jupiter is given by WASP-19. Like WASP-18, WASP-19 has a close-in hot Jupiter that orbits in less than one day. However, WASP-19 is a K type star with a deep convective zone and has a planet of almost the mass of Jupiter. WASP-19 shows high chromospheric emission, at a level similar to HD 189733 (Knutson et al. 2010). The ratio H_t/H_p in WASP-19 is 18% and the height of the tide is 55.2 km, a very small fraction of the depth of the convective zone in this star. We argue that the different stellar structure of WASP-19 and WASP-18 likely results in different dynamo strength and coronal emission. We argue that in the case of WASP-19 the tidal interaction cannot affect significantly the motions of material inside the convective zone as in the case of WASP-18. As a consequence, a magnetic dynamo can be still established and magnetic SPI is at work in this system enhancing the overall activity of WASP-19. With opposite effects, the tidal interaction of WASP-18b takes over the magnetic influence and suppresses the magnetic dynamo of WASP-18.

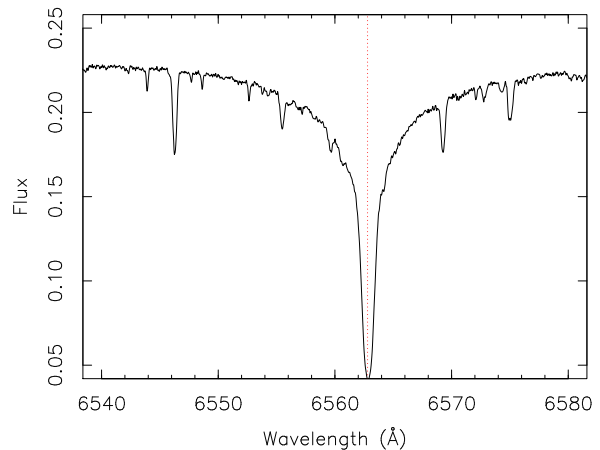


Fig. 2. Portion of FEROS spectrum of WASP-18 around $H\alpha$ from the ESO archive of pipeline reduced spectra. This particular spectrum was taken on Sept 19th 2010. We use arbitrary units for flux on Y axis. Absence of core emission in $H\alpha$, and narrow lines support the idea that the star is not as young as Hyades and is a moderately high rotator.

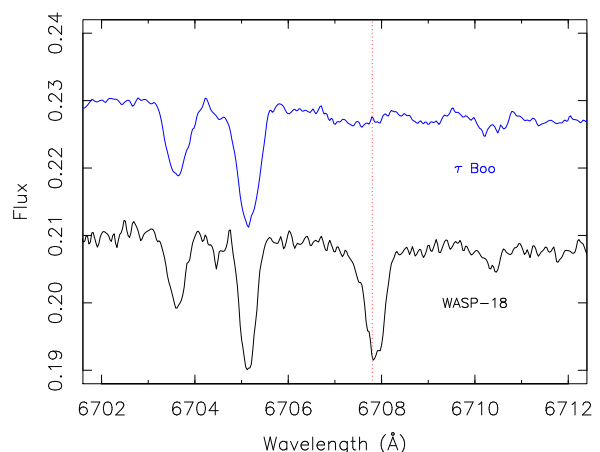


Fig. 3. Portion of FEROS spectrum of WASP-18 around Li doublet at 6707.8\AA . This particular spectrum has been taken on Sept 19th 2010. We use arbitrary units for flux on Y axis. For comparison we plot also the FEROS spectrum of τ Boo in the same spectral range. The spectrum of τ Boo has been scaled and shifted in wavelength of $+0.42\text{\AA}$ (accounting for its radial velocity) for an easier comparison with WASP-18. The Li feature is strong in WASP-18 and absent in τ Boo.

In summary, the factors that lead to SPI are not only a function of planet-star separation and planet/star mass ratio, but rely also on the inner structure of the parent star, the efficiency of its dynamo, its age and the strength of a planetary magnetic field.

6. Summary and conclusions

Aimed to detect effects of star-planet interaction at high energies, we have analyzed a 87 ks deep *Chandra* observation pointed toward the star with hot Jupiter WASP-18. We do not find X-ray

Table 3. Properties of stars with hot Jupiter s with T_{eff} in the range 6200 – 6600 K. We list the effective temperatures, stellar masses and radii, planet-star separations, chromospheric activity indicator $\log R'_{HK}$ (from Knutson et al. 2010), pressure scale heights (H_P), tidal heights (H_t) and ratio H_t/H_P based on the formulae given by Cuntz et al. (2000). Stellar data are taken from exoplanets.eu catalog and ordered by decreasing H_t/H_P ratio. Data of WASP-19 are shown because of the planet-star separation very similar to WASP-18. WASP-18 is the only star with pressure scale height and tidal height of the same order of magnitude. The second highest H_t/H_P ratio ($\sim 20\%$) is seen in WASP-12, which has a low activity like WASP-18.

Star	T_{eff} K	R_{star} R_\odot	M_{star} M_\odot	M_{planet} M_{Jup}	Separation AU	$\log R'_{HK}$	H_P km	H_t km	H_t/H_P
WASP-18	6400	1.29	1.28	10.43	0.02047	-5.43	419	498.3	1.189
WASP-12	6300	1.599	1.35	1.404	0.02293	-5.5	600.1	122.3	0.204
WASP-14	6475	1.306	1.211	7.341	0.036	-4.923	458.7	44	0.096
XO-3	6429	1.377	1.213	11.79	0.0454	-4.595	505.5	39.4	0.078
HAT-P-7	6350	1.84	1.47	1.8	0.0379	-5.018	735.5	37.2	0.051
HAT-P-2	6290	1.64	1.36	8.74	0.0674	-4.78	625.6	14.6	0.023
Kepler-5	6297	1.793	1.374	2.114	0.05064	-5.037	740.9	14.1	0.019
HAT-P-14	6600	1.468	1.386	2.2	0.0594	-4.855	516	3.4	0.007
HAT-P-6	6570	1.46	1.29	1.057	0.05235	-4.799	545.9	2.6	0.005
Kepler-8	6213	1.486	1.213	0.603	0.0483	-5.05	568.8	2.3	0.004
WASP-17	6650	1.38	1.2	0.486	0.0515	-5.331	530.7	1.1	0.002
HAT-P-9	6350	1.32	1.28	0.67	0.053	-5.092	434.7	1	0.002
WASP-19	5500	1.004	0.904	1.114	0.01616	-4.66	308.5	55.2	0.179

Table 4. Optical and IR counterparts of X-ray sources. The first part of the Table lists the six NED counterparts, the second part lists the two 2MASS counterparts, the third part lists the only Simbad counterpart.

#	RA (deg)	Dec (deg)	No.	NED name		RA(deg)	DEC(deg)	Type	Magnitude	Separation			
X-ray pos.											and Filter	arcsec	
20	24.29519	-45.57693	62	APMUKS(BJ)	B013505.04-454952.2	24.29543	-45.57682	G	18.99	0.7			
22	24.3018	-45.60976	30	MRSS	244-010213	24.30153	-45.60971	G	18.9r	0.7			
129	24.35544	-45.66886	6	APMUKS(BJ)	B013519.66-455523.1	24.3557	-45.66886	G	20.29	0.7			
131	24.3612	-45.67118	5	APMUKS(BJ)	B013520.98-455532.3	24.36116	-45.67142	G	19.67	0.9			
184	24.49494	-45.65133	49	MRSS	244-008106	24.49512	-45.65108	G	18.0r	1.0			
186	24.50386	-45.75107	70	APMUKS(BJ)	B013555.40-460017.6	24.5036	-45.75096	G	19.55	0.8			
#	RA	Dec	RAJ2000	DEJ2000	2MASS name	Jmag	e_Jmag	Hmag	e_Hmag	Kmag	e_Kmag	Qflg	Sep.
20	24.29519	-45.57693	24.295321	-45.577065	01371087-4534374	16.6	0.14	15.9	0.13	15.2	0.16	BBC	0.6
184	24.49494	-45.65133	24.494989	-45.65136	01375879-4539048	16.74	0.154	15.80	0.15	15.0	0.13	BBB	0.2
#	RA	DEC	Simbad ID	OTYPE	pmRA	pmDEC	Plx_VALUE	Z_VALUE	B	V	SP_TYPE	Sep.	
211	24.743367	-45.774851	HD 10210	Star	48.35	-1.45	6.33	4.8E-5	9.02	8.08	G8III/IV	1.6	

Table 5. Best fit models and parameters. We used absorbed powe law as model (Abs+Pow) for all but two cases, where we used absorbed bremsstrahlung (src. # 64, Abs+Brem) and two thermal modela (src. # 211, Apec+Apec). Errors are given at 1σ level.

#	Model name	χ^2	D.o.F.	N_H	$\text{err}(N_H)$ cm ⁻²	kT/α	$\text{err}(KT/\alpha)$ keV/-	Norm	$\text{err}(\text{Norm})$ cm ⁻⁵	flux erg s ⁻¹ cm ⁻²		
8	Abs+Pow	2.82	6	0.10	0.22	1.8	0.5	4.2e-06	2.0e-06	2.0e-14		
20	Abs+Pow	4.13	4	0.35	0.50	0.51	0.5	1.8e-06	1.3e-06	4.0e-14		
22	Abs+Pow	4.13	4	0.35	0.5	0.5	0.5	1.8e-6	1.2e-6	5.4e-14		
57	Abs+Pow	9.7	5	0.4	0.3	3.5	0.8	1.7e-05	1.0e-05	1.7e-14		
64	Abs+Brems	13.0	10	0.61	0.27	4.9	2.9	1.33e-05	4.1e-06	3.5e-14		
90	Abs+Pow	6.91	3	4.6	1.9	2.9	1.0	4.3e-05	5.8e-05	1.8e-14		
104	Abs+Pow	4.51	6	0.13	0.16	1.9	0.4	5.5e-06	2.1e-06	2.2e-14		
135	Abs+Pow	0.45	1	1.2	0.8	2.1	0.8	4.4e-06	4.8e-06	9.6e-15		
145	Abs+Pow	0.96	1	0.02	0.20	1.8	0.5	1.6e-06	0.9e-06	9.0e-15		
182	Abs+Pow	2.35	2	0.0	0.2	1.6	0.5	1.7e-06	0.9e-06	1.2e-14		
190	Abs+Pow	0.22	3	0.0	0.23	1.5	0.5	4.3e-06	2.3e-06	3.1e-14		
#	Model	χ^2	D.o.F.	kT_1	$\text{err}(KT_1)$	kT_2	$\text{err}(KT_2)$	Norm1	$\text{err}(\text{Norm1})$	Norm2	$\text{err}(\text{Norm2})$	flux
211	Apec+Apec	41.1	36	0.37	0.06	0.75	0.1	4.1e-5	2.0e-5	2.7e-5	1.7e-5	9.1e-14

emission from the star at a level above $L_X = 4.5 \times 10^{26}$ erg s⁻¹. The star is at least 2.5 orders of magnitude less luminous in X-rays than analogs F late stars in Hyades, and main sequence stars like τ Boo, the 4 Gyr old star HD 110450 and Procyon, which is at the very end of the main sequence or already post main sequence. The absence of X-ray activity is in agreement with the low chromospheric activity reported by Knutson et al. (2010), with the absence of reversal core emission in H α and Ca H&K line. These facts strongly conflict with the estimate of the

age from fitting to isochrones (600 Myr) given by Hellier et al. (2009) and Southworth et al. (2009), and the strong Li absorption observed in optical spectra and would suggest an activity level more consistent with a solar age.

A stellar age of a few Gyr puts strong constraints on the evolution model of the planet. In particular, it implies that the inward planet migration took place on a time scale of a few Gyr, not on time scale of hundreds of Myr as assessed by Brown et al.

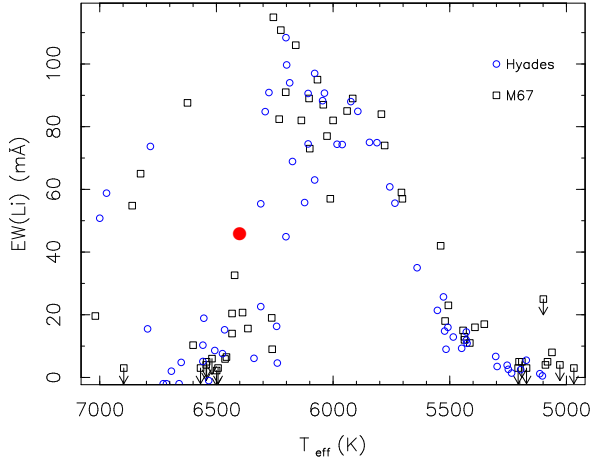


Fig. 4. EWs of Li vs. T_{eff} for Hyades (open squares), M67 (open circles) and WASP-18 (filled circle). The EW(Li) of WASP-18 is $EW = 46 \pm 2$ mÅ and suggests a young age like Hyades, in contradiction with the absent activity of its corona and chromosphere.

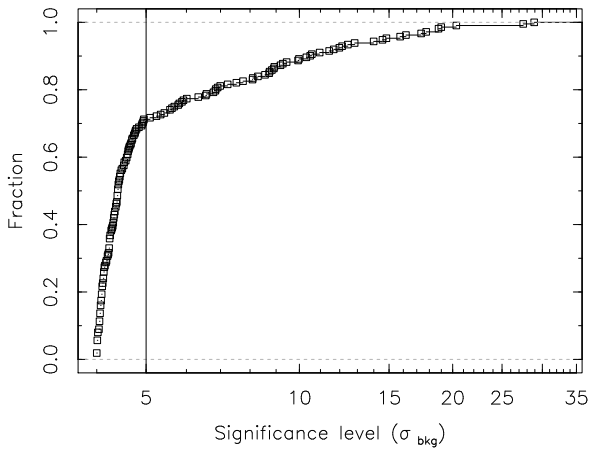


Fig. 5. Cumulative distribution of significance in σ_{bkg} . Scale on x-axis is log. A break at a significance level $\sigma = 5$ is noticed.

(2011). Hence, the orbital evolution of WASP-18 b may have been slower than predicted by models.

The absence of X-rays activity in the star indicates also a null efficiency of the magnetic dynamo. In these conditions, magnetic SPI is not at work, but rather, a strong tidal influence from the massive hot Jupiter can have a major role in determining the outer stellar structure and activity of WASP-18. To reconcile the strong Li absorption with an absent activity, we suggest a scenario in which the tidal interaction of the massive planet has modified the inner stellar mixing, thus preventing or at least reducing the Li burning. At the same time, the upper layers of the thin convective zone expected at this stellar mass are profoundly altered by tidal stresses. In a sample of stars with hot Jupiters in the same range of effective temperature, WASP-18 is the only object to show a tide height, induced by its planet, higher than the gas pressure scale height. The motions induced by tidal SPI

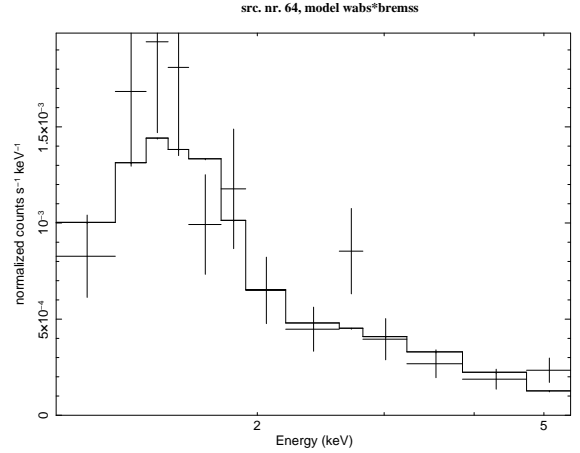


Fig. 6. X-ray spectrum and best fit model of src. 64. A line at ~ 2.5 keV is noticed.

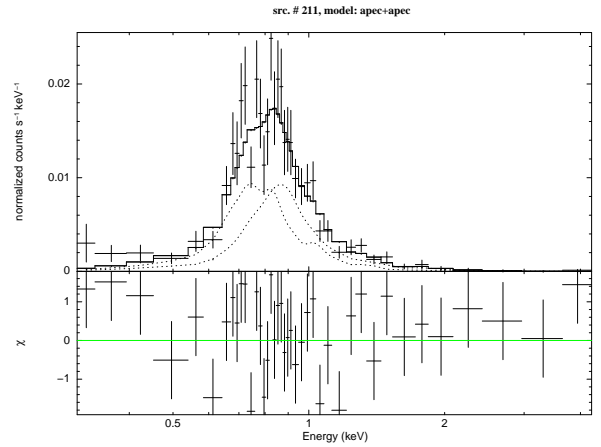


Fig. 7. X-ray spectrum and best fit model of the G8III/IV star HD 10210 (src. # 211). A thermal model with two components ($kT_1 = 0.37$ keV, $kT_2 = 0.75$) is the best fit to the spectrum.

could reduce the shear within the convective zone, hampering the creation of a magnetic dynamo and thus the outer corona and the production of X-rays. The same tides could be responsible for a reduction of the mixing efficiency in the inner layers resulting in a higher Li abundance than observed in stars of similar mass, like τ Boo. This hypothesis requires detailed simulations in the framework of two bodies interaction and modification of the stellar structure in binary systems. Our results can be a stimulus to understand any of these effects, and highlight the uniqueness of WASP-18 among systems with hot Jupiters.

We find 212 X-ray sources in the ACIS image. We briefly discuss their characteristics in the Appendix.

Acknowledgements. IP and SJW are grateful to dr. S. Saar for his comments on this paper. IP acknowledges financial support of the European Union under the project “Astronomy Fellowships in Italy” (AstroFit). S.J.W. was supported by NASA contract NAS8-03060. VA is grateful to dr. R. Trampedach for the discussion about the models of stellar convection. VA acknowledges funding for the Stellar Astrophysics Centre provided by The Danish National Research Foundation; the research is supported by the ASTERISK project (ASTERoseismic In-

vestigations with SONG and Kepler) funded by the European Research Council (Grant agreement no. 267864).

References

- Baliunas, S. L., Donahue, R. A., Soon, W. H., et al. 1995, *ApJ*, 438, 269
- Bouvier, J. 2008, *A&A*, 489, L53
- Brown, D. J. A., Cameron, A. C., Hall, C., Hebb, L., & Smalley, B. 2011, *Monthly Notices of the Royal Astronomical Society*, 415, 605
- Casagrande, L., Schönrich, R., Asplund, M., et al. 2011, *A&A*, 530, A138
- Catala, C., Donati, J.-F., Shkolnik, E., Bohlender, D., & Alecian, E. 2007, *MNRAS*, 374, L42
- Claret, A. 2004, *A&A*, 424, 919
- Claret, A. 2005, *A&A*, 440, 647
- Claret, A. 2006, *A&A*, 453, 769
- Claret, A. 2007, *A&A*, 467, 1389
- Cuntz, M., Saar, S. H., & Musielak, Z. E. 2000, *ApJ*, 533, L151
- Damiani, F., Flaccomio, E., Micela, G., et al. 2003, *ApJ*, 588, 1009
- Damiani, F., Maggio, A., Micela, G., & Sciortino, S. 1997a, *ApJ*, 483, 350
- Damiani, F., Maggio, A., Micela, G., & Sciortino, S. 1997b, *ApJ*, 483, 370
- Delgado Mena, E., Israelian, G., González Hernández, J. I., et al. 2014, *A&A*, 562, A92
- Deliyannis, C. P., King, J. R., Boesgaard, A. M., & Ryan, S. G. 1994, *ApJ*, 434, L71
- Demarque, P., Woo, J.-H., Kim, Y.-C., & Yi, S. K. 2004, *ApJS*, 155, 667
- Doyle, A. P., Smalley, B., Maxted, P. F. L., et al. 2013, *MNRAS*, 428, 3164
- Eldridge, J. J. & Tout, C. A. 2004, *MNRAS*, 353, 87
- Erkaev, N. V., Kulikov, Y. N., Lammer, H., et al. 2007, *A&A*, 472, 329
- Fares, R., Donati, J.-F., Moutou, C., et al. 2010, *MNRAS*, 406, 409
- Giardino, G., Favata, F., Pillitteri, I., et al. 2007, *A&A*, 475, 891
- Gonzalez, G. 2008, *MNRAS*, 386, 928
- Hellier, C., Anderson, D. R., Collier Cameron, A., et al. 2009, *Nature*, 460, 1098
- Holmberg, J., Nordström, B., & Andersen, J. 2009, *A&A*, 501, 941
- Houdek, G., Balmforth, N. J., Christensen-Dalsgaard, J., & Gough, D. O. 1999, *A&A*, 351, 582
- Ip, W.-H., Kopp, A., & Hu, J.-H. 2004, *ApJ*, 602, L53
- Israelian, G., Santos, N. C., Mayor, M., & Rebolo, R. 2004, *A&A*, 414, 601
- Kashyap, V. L., Drake, J. J., & Saar, S. H. 2008, *ApJ*, 687, 1339
- Knutson, H. A., Howard, A. W., & Isaacson, H. 2010, *ApJ*, 720, 1569
- Krejčová, T. & Budaj, J. 2012, *A&A*, 540, A82
- Melo, C., Santos, N. C., Pont, F., et al. 2006, *A&A*, 460, 251
- Miller, B. P., Gallo, E., Wright, J. T., & Dupree, A. K. 2012, *ApJ*, 754, 137
- Pace, G., Castro, M., Meléndez, J., Théado, S., & do Nascimento, Jr., J.-D. 2012, *A&A*, 541, A150
- Pallavicini, R., Golub, L., Rosner, R., et al. 1981, *ApJ*, 248, 279
- Penz, T. & Micela, G. 2008, *A&A*, 479, 579
- Pillitteri, I., Günther, H. M., Wolk, S. J., Kashyap, V. L., & Cohen, O. 2011, *ApJ*, 741, L18
- Pillitteri, I., Wolk, S. J., Cohen, O., et al. 2010, *ApJ*, 722, 1216
- Pillitteri, I., Wolk, S. J., Lopez-Santiago, J., et al. 2014, *ArXiv e-prints*
- Pizzolato, N., Maggio, A., Micela, G., Sciortino, S., & Ventura, P. 2003, *A&A*, 397, 147
- Polis, O. R., Schröder, K.-P., Hurley, J. R., Tout, C. A., & Eggleton, P. P. 1998, *MNRAS*, 298, 525
- Poppenhaeger, K., Robrade, J., & Schmitt, J. H. M. M. 2010, *A&A*, 515, A98+
- Poppenhaeger, K. & Schmitt, J. H. M. M. 2011, *ApJ*, 735, 59
- Poppenhaeger, K., Schmitt, J. H. M. M., & Wolk, S. J. 2013, *ApJ*, 773, 62
- Poppenhaeger, K. & Wolk, S. J. 2014, *ArXiv e-prints*
- Randich, S. & Schmitt, J. H. M. M. 1995, *A&A*, 298, 115
- Randich, S., Singh, K. P., Simon, T., Drake, S. A., & Schmitt, J. H. M. M. 1998, *A&A*, 337, 372
- Saar, S. H., Cuntz, M., & Shkolnik, E. 2004, in *IAU Symposium*, Vol. 219, *Stars as Suns : Activity, Evolution and Planets*, ed. A. K. Dupree & A. O. Benz, 355–+
- Sanz-Forcada, J., Micela, G., Ribas, I., et al. 2011, *A&A*, 532, A6
- Schröter, S., Czesla, S., Wolter, U., et al. 2011, *A&A*, 532, A3+
- Shkolnik, E., Walker, G. A. H., & Bohlender, D. A. 2003, *ApJ*, 597, 1092
- Skumanich, A. 1972, *ApJ*, 171, 565
- Soderblom, D. R. 2010, *ARA&A*, 48, 581
- Southworth, J., Hinse, T. C., Dominik, M., et al. 2009, *ApJ*, 707, 167
- Stern, R. A., Schmitt, J. H. M. M., & Kahabka, P. T. 1995, *ApJ*, 448, 683
- Takeda, Y., Honda, S., Ohnishi, T., et al. 2012, *ArXiv e-prints*
- Thorburn, J. A., Hobbs, L. M., Deliyannis, C. P., & Pinsonneault, M. H. 1993, *ApJ*, 415, 150
- Torres, G., Winn, J. N., & Holman, M. J. 2008, *ApJ*, 677, 1324
- Trampedach, R., Asplund, M., Collet, R., Nordlund, Å., & Stein, R. F. 2013, *ApJ*, 769, 18
- Vaughan, A. H. & Preston, G. W. 1980, *PASP*, 92, 385
- Walker, G. A. H., Croll, B., Matthews, J. M., et al. 2008, *A&A*, 482, 691
- Wilson, O. C. 1966, *ApJ*, 144, 695
- Yi, S., Demarque, P., Kim, Y.-C., et al. 2001, *ApJS*, 136, 417

Appendix A: Nature of the X-ray sources

In the ACIS image we have detected 212 X-ray sources with significance $> 4\sigma$. We have cross matched their spatial positions with Simbad, NED, and 2MASS catalogs within a positional separation of $2''$, obtaining seven matches that are listed in Table 4. All NED matches are galaxies, and the X-ray emission could be associated to the AGNs at their center. One match is the giant/sub-giant G8III/IV star (HD 10210, src # 211) with $V = 8.08$. The two matches in 2MASS are again two galaxies in NED catalog.

We are left with 205 X-ray sources with unknown match in the above catalogs. Most of these sources are faint as shown by the cumulative distribution of the significance values (Fig. 5). The cumulative distribution has a change of slope at about $\sigma = 5$, marking the brighter sample from the rest of the sources. The number of unidentified sources with $\sigma > 5$ is 55, or the 27% of the total sample. A number of them could be distant AGNs.

For the brightest sources we did a model best fit to the spectra with one absorbed powerlaw, suited in the case of AGNs and well describing the featureless spectra that we observe in these sources. In the bright source # 64 we find a good best fit with an absorbed bremsstrahlung, but the presence of a line at ~ 2.5 keV is also noticed.

The G8III/IV type star HD 10210 is also detected as the brightest in the sample (source # 211). The best fit of the spectrum of HD 10210 has two temperatures at $kT = 0.37$ and $kT = 0.75$, with the cool component weighting twice than the hot component in the spectrum. Overall, the spectrum is similar to that of a mid active main sequence star. Detecting X-ray emission in a evolved star off of the main sequence is worth to be noticed, its X-ray luminosity is $L_X \sim 1.1 \times 10^{29}$ erg/s.